Battery Management System (BMS) Evaluation Toolset
Final Report

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Executive Summary

The military is currently pursuing the development of advanced battery systems for ground vehicles. Battery Management Systems (BMS) are required for safe operation and performance optimization. The military will utilize technologies from any qualified source, so battery electronics may widely vary. Consequently, the military has the need to develop standard protocols for evaluating BMS using modeling and hardware in the loop simulation.

To this end, the goal of this project has been to develop the capability to independently test and evaluate Battery Management Systems for the Army and to use this capability to test an existing BMS. Under this project, the U.S. Army TARDEC has acquired a Hardware-in-the-Loop (HIL) battery pack simulator which is capable of imitating the voltage profiles of lithium ion battery cells. The system was calibrated and a terminal block system was built to easily connect the HIL to future BMS that the Army needs to test. We utilized the HIL to examine a BMS that was part of a battery module developed under a previous program. The voltage simulators of the HIL were used to simulate the seven cells in that module and replicate all possible faults the BMS was designed to detect. Additionally, the HIL was used to simulate battery charges and discharges so that the output data of the BMS could be compared to the output of the HIL for accuracy. Finally, we repeated this testing with the BMS in a cold temperature chamber to see if the performance of the BMS was affected. Through this process, we have successfully developed a methodology for evaluating future Battery Management Systems and we were able to apply this methodology to a sample BMS. The fundamental BMS tests, procedures and BMS HIL guidance that we developed in this effort will provide valuable lessons-learned to build on in future, more comprehensive BMS investigations.

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Introduction and Problem Statement

In order to support the high demand for energy in future systems, the military is currently developing advanced lithium ion battery technologies. Lithium ion batteries offer significant advantages over conventional lead acid systems in terms of both energy and power capability. However, these advantages are not without liabilities. Lithium ion battery chemistries are much more energetic and are capable of catching fire when mistreated. As a result, batteries based on these chemistries require Battery Management Systems (BMS) in order to both optimize their performance and ensure they are not put into unsafe operating conditions. These systems can monitor individual cells and cell stacks to identify negative conditions, such as overcharging or cell-to-cell imbalances. Depending on the nature of the issue, BMS systems may be able to correct them, send a warning to the user, or shut down the battery to prevent harm.

A BMS can be designed to provide a variety of functions from very simple voltage monitoring to advanced state of health tracking. Some BMS functions are critical to the safe operation of batteries like the prevention of over-voltage/charging while the need for other functions depend on the application, such as communicating battery status back to a vehicle or user. The table below provides a list of BMS capabilities of interest to the Army for ground vehicle systems and indicates the functions we tested for under this project.

Table 1 – Desired BMS Functions

Battery Management System Function	Tested?
Measure Cell/Battery Voltages	X
Measure Cell/Battery Currents	
Measure Cell/Battery Resistances	
Measure Cell/Battery Temperature	
Report any/all of the above measurements to the vehicle/user	X
Report battery State-of-Charge to the vehicle/user	
Report battery State-of-Health to the vehicle/user	
Prevent Battery or Cell over-voltage/over-charge	X
Prevent Battery or Cell under-voltage/over-discharge	X
Detect Cell-to-Cell imbalances	X

Balance Cells	X
Detect dangerous temperature conditions in the cell stack and shut down system to prevent damage	
Detect dangerous pressure conditions in the cell stack and shut down system to prevent damage	X

Because of the need for BMS in advanced batteries, the military has strong interest in the capability to test and evaluate these systems. Currently, the U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC) evaluates battery systems by testing battery modules and packs with electrochemical cells and BMS integrated in one unit. While this strategy can determine a lot about the operation and performance of the battery system, it is ineffective at analyzing the performance of the BMS itself. This is due to the fact that it is unlikely that the BMS will encounter many of the issues it is designed to detect and prevent during normal operation of the device and it is difficult to induce any of these conditions with actual electrochemical cells. Moreover, replicating these conditions with actual electrochemical cells will create a dangerous situation in the laboratory by exceeding cell safety limits in order to determine how the BMS will respond. Therefore, strategies for testing the BMS independently of any electrochemical cells are required.

To answer this need, this project had two main objectives:

1. Develop the laboratory capabilities to independently test and evaluate Battery Management Systems for ground vehicle applications. This capability includes new hardware and software for simulating battery cells as well as the procedures necessary to verify the performance of the BMS.
2. Utilize this new capability to examine a BMS from a previous U.S. Army TARDEC project. TARDEC has never before been able to analyze a BMS in this fashion.

Battery Test Module Basic Information

The BMS being tested under this effort was extracted from a 7-cell Lithium-Manganese-Spinel battery module, which uses RS-232 for communication of battery cell voltages. Existing test data was available for this battery module and its constituent cells; however, the precision of this data was not sufficient to generate the lookup table required by the BMS HIL. Rather, generic data from another Lithium-Manganese cell was utilized to populate the BMS HIL's battery cell

model. The BMS in these battery modules detect both cell voltages and temperatures and provides active cell balancing.

Figure 1 - Battery Cell

Figure 2 - 28-V, 7-Cell Lithium-Manganese-Spinel Module

BMS HIL Basic Information

The BMS HIL is a highly flexible system for the real time simulation of the electrical and thermal properties of a battery down to the cell level for the evaluation of BMS's. The HIL test system can be used to independently evaluate/validate BMS under a variety of environmental conditions. The HIL test system being used for this project has the following characteristics:

- The system is capable of evaluating BMS for isolation monitoring, voltage monitoring, current monitoring, temperature sensing and cell balancing.
- The system is capable of simulating electrical failures (including broken/loose connections and isolation failure)
- The system has 180 cell simulators and is capable of emulating up to 16 temperature readings.
- Each cell simulator provides a galvanically isolated voltage from 0 to 5V in 2mV increments and is capable of handling a 150 mA load.
- Individual cell simulators are capable of being connected in series to simulate a full pack with a nominal voltage of 600V DC (with a maximum voltage of at least 750V DC).

- The HIL test system provides 25 independent voltage measurements.
- The system provides 24V to power the BMS during testing.
- Communication between the HIL system and BMS is via Serial and/or controller area network (CAN).

Critical Task Descriptions (See Project Plan for timeline):

- Checkout of battery module communications hardware/software
    - In this task, we confirmed the BMS in the battery module was properly communicating via RS232 to our laboratory PC's while the battery cells were still present.

- Removal of cells from battery module
    - Once communication was established with the BMS with cells present, the 7 series cells in the stack were removed from the battery module and communications with the BMS were re-established after power-up by external power supply.

- Creation of wire harness for connection to BMS
    - Using documentation from the BMS HIL vendor, a wire harness was created to interface between the BMS and BMS HIL. This wire harness was of basic construction using twisted wires and alligator clips as the test fixture only require nine wire connections and the BMS HIL cell simulators were delivered as bare wires. It was noted that this method of connection would not be sufficient for future battery wire harnesses, so a terminal blocking system was designed, purchased, and assembled for use with future BMS's.

- Develop basic test plans and procedures for HIL testing
    - Using existing Lab test plans and procedures, a basic test plan and procedure was developed for the BMS HIL testing.

- Collect previous battery module test data to generate lookup table
    - Existing cell and module data acquired from previous testing of the test battery module and constituent cells could not be used to generate a look-up table with the necessary parameters to populate the BMS HIL model because of insufficient precision of data. Instead, data from another representative Lithium-Manganese cell was utilized to populate the BMS HIL's battery cell model. This data was chosen as it fit within the general BMS parameters and was close in value to the cell data though with greater precision. This data can be seen in Appendix G – Cell Model.

- BMS HIL Testing (Room Temperature)
    - BMS functionality was assessed at room temperature according to the previously developed test plans and procedures. Photographs were taken as appropriate.

- BMS HIL Fault testing (Room Temperature)

  - Simulated faults were applied the cell simulators connected to the BMS to determine the BMS's response to these events.

- BMS HIL Testing (Cold-Temperature)
  - BMS functionality was assessed at cold temperature according to the previously developed test plans and procedures. Photographs were taken as appropriate. This testing matched the room temperature scope and duration and focused on determining whether the BMS functionality would be impaired by cold-temperature.

Battery Disassembly & BMS Extraction

Prior to disassembly of the battery module for BMS extraction, a number of activities were undertaken to allow future reassembly as well as to document the initial state of the BMS and Battery Module. Communication via RS-232 was established with the module to allow a check whether the module was still functioning and to establish a baseline understanding of the BMS's accuracy and precision in reporting cell voltages. The measured and BMS cell voltages are reported in Table 2. This data showed that the maximum absolute difference between the measured cell voltage and BMS reported voltage was around 0.004 V. The serial #'s and other relevant characteristics observable from a visual study of the BMS were also recorded.

Table 2 - BMS and Cell Data Baseline

Cell #	Serial #	Voltage (Measured)	Voltage (BMS/RS232)	Difference (Absolute)
7	3HH04C246	3.342	3.339	0.003
6	3HH04C247	3.358	3.356	0.002
5	3HH04C248	3.359	3.356	0.003
4	3HH04C249	3.359	3.356	0.003
3	3HH04C250	3.360	3.361	0.001
2	3HH04C251	3.361	3.365	0.004
1	3HH04C252	3.359	3.356	0.003

After verification of the BMS's communication functionality, the battery cells were removed from the module. Figure 3 shows a pictorial representation of the battery disassembly process. Photographs were taken as each part was removed from module and the parts were stored in individually labeled plastics bags to ensure the product could be reassembled if necessary in the future. The color coding of each cell sensor was marked and recorded to allow proper hookup of the BMS to the BMS HIL. This color coding and wiring map can be seen in Table 3. Additionally, the cell pressure sensor mechanism was studied using a volt meter and was determined to be using a micro-switch that was normally closed and that would open on

depression, thus allowing all pressure switches to be connected in series with break in the line representing an overpressure event.

Table 3 - Battery Module/BMS Sensor Wire Map

End	1	Brown
1	2	Red
2	3	Orange
3	4	Yellow + Black Thermocouple
4	5	Green
5	6	Blue
6	7	Purple
7	End	Gray

The BMS and battery module were furthered disassembled such that the BMS and battery module frame was sufficiently small enough to fit within the 1 cubic foot environmental chamber available for use. It was also noted, that the BMS power and top of stack voltage sensor were connected via the same wire. This made it impossible to power the BMS while simultaneously applying a simulated cell voltage. Therefore, it became necessary to modify the internal wiring of the BMS to allow a separation of the BMS power connection from the top of stack sense lead. The proper node in the BMS wiring was identified where the sense and power leads diverged and the power line was clipped such that external power could be applied by the BMS HIL's BMS power supply without applying this electronics power voltage to the voltage sense lead and circuitry. The BMS power supply was then set at 26.6V, 1A as this had been determined to provide an appropriate level of voltage to the BMS for operation. This voltage was kept constant over all testing.

Figure 3 – Battery Module Disassembly Process Photographic Documentation: Left Side of Module (Upper Left); Back Side of Module (Upper Right); Right Side of Module (Middle Left); Close-up of Cell Buss bar and Temperature and Voltage Sensor Wires (Middle Right); Contactor and BMS Electronics Board (Bottom Left); and Module Complete Cell Stack (Bottom Right)

BMS HIL Testing

Once the BMS power supply connections were isolated, the BMS HIL was set up and a rudimentary harness was constructed using alligator clips and wire twisting (see Figure 4). The BMS simulator channels 1 through 7 were selected, and the cell simulators were connected in series to achieve the full simulated stack voltage. The voltage sense leads extracted from the

module and coming from the BMS were then connected to the appropriate simulated cell-to-cell connections, per Table 3, to fully simulate the battery pack. The BMS HIL was then powered on and the necessary simulated channels were activated to a constant voltage. Communication with the BMS was then checked to ensure that reasonable voltages were being observed. Communication was successfully achieved through a special GSYUSAS RS-232 communications box, seen in Figure 5. This RS232 connection allowed data to be collected and logged directly from the BMS. A sample of data from this source can be seen in Appendix A - BMS RS-232 Sample Data File Excerpt.

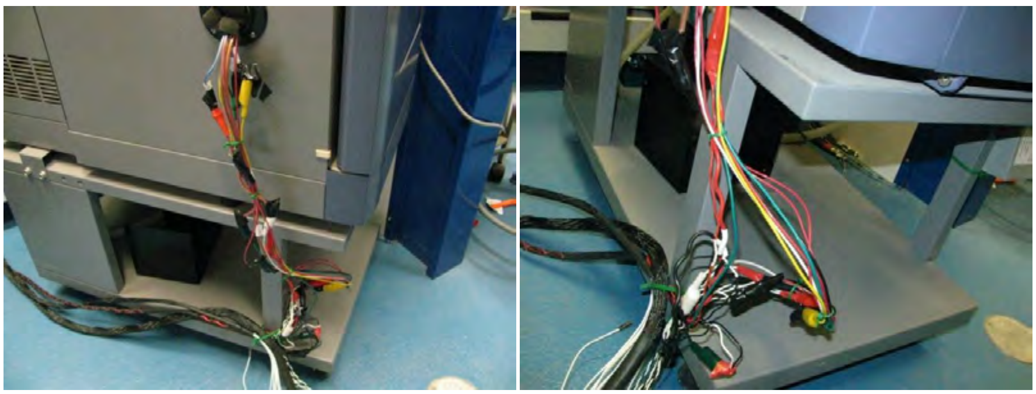


Figure 4 - BMS HIL Harness (Left); BMS HIL Harness Close-up (Right)

Figure 5 - RS-232 Communication Box

Once communications were confirmed, the general laboratory test plan and test procedure were defined for the BMS (see Appendix H – BMS HIL Experimental Test Plan and Appendix I – BMS HIL Experimental Test Plan). Based on this test plan & procedure, a test parameter table, Table 4, was generated and included constant charging and discharging profiles for the BMS at room temperature and slightly above the maximum cold temperature the unit could handle (25

°C and -18 °C). The extracted BMS was inserted into an environmental chamber to regulate temperature (see Figure 6 and Figure 7). The BMS HIL was then run using all of the test parameters and data was collected and logged from both the BMS HIL and BMS for comparison. A screenshot of the BMS HIL's built-in graphical user interface (GUI) can be seen in Appendix E – BMS HIL Graphical User Interface Screen Shot.

Table 4 - BMS Test Parameters

Temperature	Rate	Duration	SOC Start	SOC End
Discharge (Room Temperature)				
25 °C	-30 Amps	3600 seconds	90%	0%
25 °C	-60 Amps	1800 seconds	90%	0%
25 °C	-120 Amps	900 seconds	90%	0%
25 °C	-240 Amps	450 seconds	90%	0%
25 °C	-1.5 Amps	3600 seconds	90%	-
25 °C	-1.5 Amps	3600 seconds	60%	-
25 °C	-1.5 Amps	3600 seconds	5%	0%
25 °C	-3 Amps	3600 seconds	90%	-
25 °C	-3 Amps	3600 seconds	60%	-
25 °C	-3 Amps	3600 seconds	10%	0%
Charge (Room Temperature)				
25 °C	30 Amps	3600 seconds	0%	90%
25 °C	60 Amps	1800 seconds	0%	90%
25 °C	120 Amps	900 seconds	0%	90%
25 °C	240 Amps	450 seconds	0%	90%
25 °C	1.5 Amps	3600 seconds	-	90%
25 °C	1.5 Amps	3600 seconds	-	60%
25 °C	1.5 Amps	3600 seconds	0%	5%
25 °C	3 Amps	3600 seconds	-	90%
25 °C	3 Amps	3600 seconds	-	60%
25 °C	3 Amps	3600 seconds	0%	10%
Discharge (Cold Temperature)				
-18 °C	-30 Amps	3600 seconds	90%	0%
-18 °C	-60 Amps	1800 seconds	90%	0%
-18 °C	-120 Amps	900 seconds	90%	0%
-18 °C	-240 Amps	450 seconds	90%	0%
-18 °C	-1.5 Amps	3600 seconds	90%	-
-18 °C	-1.5 Amps	3600 seconds	60%	-
-18 °C	-1.5 Amps	3600 seconds	5%	0%
-18 °C	-3 Amps	3600 seconds	90%	-
-18 °C	-3 Amps	3600 seconds	60%	-
-18 °C	-3 Amps	3600 seconds	10%	0%
Charge (Cold Temperature)				
-18 °C	30 Amps	3600 seconds	0%	90%
-18 °C	60 Amps	1800 seconds	0%	90%

-18 °C	120 Amps	900 seconds	0%	90%
-18 °C	240 Amps	450 seconds	0%	90%
-18 °C	1.5 Amps	3600 seconds	-	90%
-18 °C	1.5 Amps	3600 seconds	-	60%
-18 °C	1.5 Amps	3600 seconds	0%	5%
-18 °C	3 Amps	3600 seconds	-	90%
-18 °C	3 Amps	3600 seconds	-	60%
-18 °C	3 Amps	3600 seconds	0%	10%

Figure 6 - BMS HIL (Left) and Environmental Chamber (Right)

Figure 7 – BMS Board Section in Environmental Chamber

Data Logging Programming

The BMS HIL as delivered did not have built in data logging functions. Therefore, it became necessary as part of this project to code software upgrades to implement this feature. The newly developed Lab View code can be seen in Appendix D - Data Logging Code. This code allowed

the recording of all 180 cell simulator channels on the HIL at selectable log rates, including all cell SOC, voltage, and current values.

Terminal Block System

Through testing with the BMS HIL, it was determined that the alligator clip method would not work for future BMS connections. Therefore, it was decided that a more advanced and flexible strategy needed to be developed for creating simulated cell stacks and making connection to BMS's. Single and dual-layer, screw-less Terminal block components were purchased to allow the construction of a BMS HIL distribution panel. This panel houses 180 individual terminal blocks for use on the cell simulators that allow for removable output connections to be made and also allow cell strings to be made uses simple 2-pin jumper connections. The panel also has an additional three rows of single-level, one-to-two connection terminal blocks for connection and routing to custom receptacles that will be set up to cover the major BMS connectors that are used by the battery and BMS industries. A picture of the start of this terminal block panel can be seen in Figure 8.

Figure 8 - Terminal Block System

HIL Applied Voltage Checkout

As a result of testing, it was noted that the reported voltages for the simulated cells were significantly different between the BMS and BMS HIL data. This was initially attributed to a voltage drop on the BMS HIL cables. However, this hypothesis was tested and found to be incorrect. The BMS HIL set voltages and actual voltages were very close to one another when

measured at the point of connection to the BMS sense leads (see Table 5). It is now believed that the discrepancy is possibly the result of a build-up of error as cell voltages are computed via subtraction of values measured at different points along the stack.

Table 5 - BMS HIL Set Voltage vs. Actual Voltage

Cell #	Applied Voltage	Measured Voltage
7	3.9	3.896
7	3.5	3.496
7	2.3	2.296
7	4.3	4.297
6	3.9	3.896
6	3.5	3.496
6	2.3	2.296
6	4.3	4.297
5	3.9	3.897
5	3.5	3.496
5	2.3	2.295
5	4.3	4.297
4	3.9	3.897
4	3.5	3.497
4	2.3	2.296
4	4.3	4.298
3	3.9	3.898
3	3.5	3.497
3	2.3	2.297
3	4.3	4.299
2	3.9	3.898
2	3.5	3.499
2	2.3	2.299
2	4.3	4.299
1	3.9	3.899
1	3.5	3.499
1	2.3	2.299
1	4.3	4.300

Fault Testing

BMS fault testing was also performed. Using the data from the manufacture on different maximum and minimum set points for the BMS, the BMS HIL was used to apply voltages that would result in exceeding the values of these limits. The observations for these different results are contained in Table 6. From this testing, it is clear that the BMS functioned as appropriate.

The BMS shut off completely if safety limits were tripped and gave proper warnings when cells were entering undesirable conditions, such as cell imbalance. Charge control activated in some instances due to small errors in the voltage readings by the BMS, however, the system successfully shutdown under all unsafe conditions.

Table 6 - BMS Fault Data

Faults	1	2	3	4	5	6	7
Upper Cell Voltage Limit	Shut Off	Shut Off	Shut Off	Shut Off	Shut Off	Shut Off	Shut Off
Lower Cell Voltage Limit	Shut Off	Shut Off	Shut Off	Shut Off	Shut Off	Shut Off	Shut Off
Maximum Stack Voltage	Shut Off	Shut Off	Shut Off	Shut Off	Shut Off	Shut Off	Shut Off
Low Voltage Warning	Pre-Alarm	Pre-Alarm	Pre-Alarm	Pre-Alarm	Pre-Alarm	Pre-Alarm	Pre-Alarm
Cell Imbalance	Pre-Alarm	Pre-Alarm	Pre-Alarm	Pre-Alarm	Pre-Alarm	Pre-Alarm	Pre-Alarm
Cells Balanced	Pre-Alarm	None	None	None	None	None	None
Overcharge Limit	None	Charge Control	None	None	None	None	Charge Control
Within Voltage	None	None	None	None	None	None	None

Test Results

Over 600 MB of data was collected for the various tests performed using the BMS HIL. The results for each test were very similar so only one case has been considered here for example purposes: the -60 amp (2C) discharge for cold and room temperatures. The data itself was on the proper order for both the BMS HIL and the BMS itself. It was noted that the voltages reported by the BMS for cell 1 and 7 were very different between the BMS HIL and BMS data. However, the BMS voltages of cells 2-6 measured closely to the voltages reported by the BMS HIL. Graphs for the BMS HIL and BMS data for the two temperatures can be found in Appendix F – Test Data Graphs for -60 Amps at Room Temperature and Cold Temperature. It was also recognized that the BMS HIL curves were much smoother than the BMS curves. This is most likely due to noise in the voltage sensor measurement, error in subtraction of cell stack voltages to determine individual cell voltages, sensor precision and accuracy, and data bits used for the CAN transmission of data. It should also be noted that voltage data between the test temperatures was very similar and there was not much error induced by operating the board at cold temperature.

Conclusion

Summary of Work

In the course of this effort, we were able to successfully demonstrate the ability to integrate a prototype BMS with US Army TARDEC's BMS HIL battery simulator for testing and evaluation purposes. We extracted a the BMS from a prototype lithium-ion module developed for TARDEC, and developed a modular interface for the BMS voltage sensors, cell over-pressure switches, power connections, and other BMS inputs/outputs to the BMS HIL battery simulator unit that will be used in future TARDEC BMS test and evaluation activities. Procedures for battery teardown and BMS extraction, testing, and reporting were developed to direct the BMS test and evaluation activity.

By simulating battery performance using the BMS HIL, we were able to test and evaluate various capabilities of the BMS hardware at room and cold temperatures according to the battery manufacturer's specifications. In the initial checkout test, we verified the functionality of the BMS to detect over-pressure conditions by simulating the over-pressure switch using relays built into the BMS HIL. Fault management capabilities were tested by setting each simulated battery cell independently to over-voltage and under-voltage conditions. In the simulated fault tests, the BMS was able to detect over-voltage and under-voltage faults in each cell and respond by actuating the battery stack relay that would prevent damage to the system. We were also able to investigate the capability of the BMS to manage cell imbalance within the cell stack. When we simulated imbalance within the cell stack, the BMS detected the imbalance and the state of the cell stack (charge, discharge, or rest) and would perform balancing operation when the cell stack was either in charge or rest operation. The fundamental BMS tests, procedures and BMS HIL guidance that we developed in this effort will provide valuable lessons-learned to build on in future, more comprehensive BMS investigations.

Recommended Changes to the System

We recommend the integration of the following capabilities to the BMS HIL battery simulator system:

- Current sensor emulation for coulomb counting, and emulation of other sensors, such as thermocouple.

- Collection of a library of cell test data for use in the BMS HIL
- More comprehensive battery model that reacts to dynamic conditions and BMS intervention

Currently, the BMS HIL is limited to battery voltage, discrete switch, and thermistor simulation that can be interfaced with BMS hardware. Many newer commercial-of-the-shelf BMS units rely on both voltage sensing and coulomb counting to perform battery management operations. Many units use current shunt or hall-effect sensors to perform current sensing and integration, allowing the BMS to perform coulomb counting to aid battery capacity determination. Instead of running a simulated control current through these sensors to provide current data to the BMS, these sensors could be bypassed with a voltage source that emulates the analog voltage response of these sensors expected under different load conditions, allowing the BMS to perform the coulomb counting operation. This would be hardware specific to the BMS, and would require further hardware and software capabilities to be added to the BMS to perform the sensor emulation. This method could also be used to emulate other BMS sensors, such as thermocouples.

We also recommend that a library of battery test cells be compiled and collected to be used for the BMS HIL battery models. Comprehensive characterization test data could be used to develop better models of battery cell performance, which could be incorporated into the BMS HIL. Data for a variety of cell manufacturers and cell chemistries should be compiled in a library which could be used in the evaluation universal BMS platforms that can be configured for multiple cell formats and chemistries.

In addition, a more comprehensive electrochemical model could replace the simple battery model currently used in the BMS HIL. The BMS HIL uses data from characterization and HPPC tests to develop an open-circuit voltage model with an equivalent series resistance vs. SOC to develop the cell voltage profiles used in testing. A comprehensive electrochemical model could be used to provide better dynamic simulation based on a variety of cell parameters and operational and environmental conditions. It would be useful if the BMS HIL battery simulation could respond and change during BMS intervention, such as current shuttling or selective passive

bypass-resistance on cells during balancing operation to allow the BMS to sense if the operations are performing correctly.

Recommendations for Future Efforts

Some areas we recommend for future efforts are:

- Developing BMS tests and procedures under dynamic conditions.
- Study how the BMS HIL may be used to test and verify State-of-Charge (SOC) and State-of-Health (SOH) algorithms

The tests performed in this effort were static in nature, and provided moment-in-time information on how the BMS operates. However, it will be important to understand how the BMS will react under varying load and dynamic conditions. A future effort could look into developing a dynamic battery system profile and tests to assist in testing the BMS under dynamic conditions. A critical function of for future military BMS will be SOC and SOH estimation. It will be important to investigate how the BMS HIL will interact with the SOC and SOH estimation operations of the BMS. Many commercial-of-the-shelf BMS units track the history of the battery usage and conditions the battery has operated under to aid battery models in estimating SOC and SOH. Tests that vary unrealistically to battery operation for time purposes or convenience of testing may interfere with the history logging function and provide incorrect data. For instance, if a simulation of a healthy battery is immediately followed by a simulation of a bad battery, the SOH algorithm may become erratic, since it may not be realistic for a battery to degrade that suddenly, and the degradation was not demonstrated as a trend in the history log. Other BMS may use current pulses or spectroscopy to track resistance growth within the battery, which is not currently compatible with the BMS HIL. Future efforts will need to study how SOC, SOH, and other advanced functions of the BMS will work with BMS HIL testing.

Economic Benefits

The BMS HIL provides numerous capabilities for BMS testing and evaluation, which will increase efficiency in product development and evaluation, and provide safer modes of testing battery failure. By separating the testing of the BMS from the battery pack, the BMS may be tested earlier on in development to identify design flaws before integration with the battery pack, preventing costlier modifications later in development and increasing the battery system maturity more for rapid delivery to the field. The BMS HIL also reduces safety risks of testing, by

separating the BMS testing from the possibility of battery pack failure. This enables the BMS to be tested more efficiently under less restrictive lab conditions for safety considerations, such as containment needed for battery testing in case of battery failure, which reduces the cost of testing. By testing the BMS separately from the battery pack, the possibility of damaging expensive battery packs is eliminated, especially under abuse and extreme conditions.

Appendix A - BMS RS-232 Sample Data File Excerpt

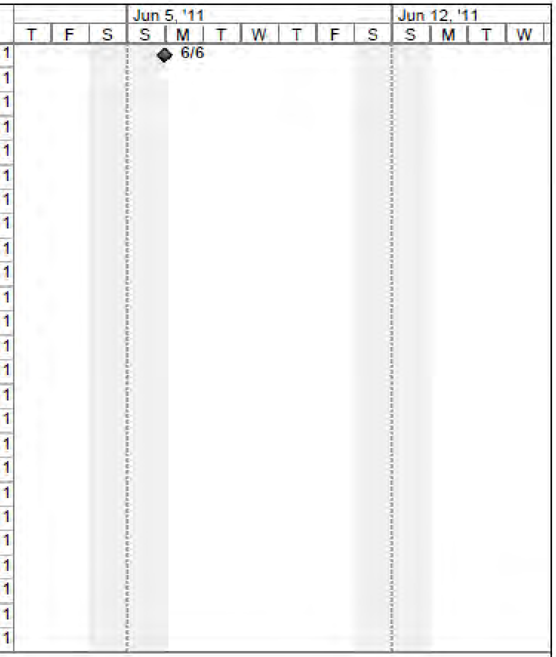
Date	Time		Cell1	Cell2	Cell3	Cell4	Cell5	Cell6	Cell7	Temp	Flag_L	Flag_H	Signal	Balancing	Elapsed_time(min)
7/28/2011	2:10:44	PM	4.024	4.05	4.037	4.037	4.037	4.042	4.055	-17	0	0	0	1	51
7/28/2011	2:10:44	PM	4.05	4.077	4.068	4.068	4.068	4.068	4.086	-17	0	0	0	1	52
7/28/2011	2:10:45	PM	4.05	4.077	4.068	4.068	4.068	4.068	4.086	-17	0	0	0	1	52
7/28/2011	2:10:46	PM	4.05	4.073	4.068	4.068	4.068	4.068	4.086	-17	0	0	0	1	52
7/28/2011	2:10:47	PM	4.05	4.073	4.068	4.068	4.068	4.068	4.086	-17	0	0	0	1	52
7/28/2011	2:10:48	PM	4.05	4.073	4.068	4.068	4.068	4.068	4.086	-17	0	0	0	1	52
7/28/2011	2:10:49	PM	4.05	4.077	4.068	4.068	4.068	4.068	4.086	-17	0	0	0	1	52
7/28/2011	2:10:50	PM	4.05	4.077	4.068	4.068	4.068	4.068	4.086	-17	0	0	0	1	52
7/28/2011	2:10:51	PM	4.05	4.073	4.068	4.068	4.068	4.068	4.086	-17	0	0	0	1	52
7/28/2011	2:10:52	PM	4.05	4.073	4.064	4.068	4.064	4.064	4.081	-17	0	0	0	1	52
7/28/2011	2:10:53	PM	4.046	4.073	4.064	4.064	4.064	4.064	4.081	-17	0	0	0	1	52
7/28/2011	2:10:54	PM	4.046	4.073	4.064	4.064	4.064	4.064	4.081	-17	0	0	0	1	52
7/28/2011	2:10:55	PM	4.046	4.073	4.064	4.064	4.064	4.064	4.081	-17	0	0	0	1	52
7/28/2011	2:10:56	PM	4.046	4.073	4.064	4.064	4.064	4.064	4.081	-17	0	0	0	1	52
7/28/2011	2:10:57	PM	4.046	4.068	4.064	4.064	4.064	4.064	4.081	-17	0	0	0	1	52
7/28/2011	2:10:58	PM	4.046	4.068	4.064	4.064	4.064	4.064	4.077	-17	0	0	0	1	52
7/28/2011	2:10:59	PM	4.046	4.068	4.064	4.064	4.064	4.064	4.081	-17	0	0	0	1	52
7/28/2011	2:11:00	PM	4.046	4.068	4.064	4.064	4.064	4.064	4.081	-17	0	0	0	1	52
7/28/2011	2:11:01	PM	4.046	4.068	4.064	4.064	4.064	4.064	4.081	-17	0	0	0	1	52
7/28/2011	2:11:02	PM	4.046	4.068	4.064	4.064	4.064	4.064	4.081	-17	0	0	0	1	52
7/28/2011	2:11:03	PM	4.046	4.068	4.064	4.064	4.064	4.064	4.081	-17	0	0	0	1	52
7/28/2011	2:11:04	PM	4.046	4.068	4.064	4.064	4.064	4.064	4.077	-17	0	0	0	1	52
7/28/2011	2:11:05	PM	4.046	4.068	4.064	4.064	4.064	4.064	4.081	-17	0	0	0	1	52
7/28/2011	2:11:06	PM	4.046	4.068	4.064	4.064	4.064	4.064	4.081	-17	0	0	0	1	52
7/28/2011	2:11:07	PM	4.046	4.068	4.064	4.064	4.064	4.064	4.081	-17	0	0	0	1	52
7/28/2011	2:11:08	PM	4.046	4.068	4.064	4.064	4.064	4.064	4.081	-17	0	0	0	1	52

Appendix B - BMS HIL Sample Data Excerpt

Time	SOC							Voltages							Currents						
8:38:31 AM	90	90	90	90	90	90	90	4.075	4.074	4.075	4.074	4.074	4.074	4.074	0	0	0	0	0.001	0	0.001
8:38:32 AM	90	90	90	90	90	90	90	4.075	4.073	4.075	4.073	4.075	4.073	4.073	0	0	0	0	0.001	0.001	0
8:38:33 AM	90	90	90	90	90	90	90	4.075	4.073	4.075	4.073	4.073	4.074	4.073	0	0	0	0	0.001	0.001	0
8:38:34 AM	90	90	90	90	90	90	90	4.075	4.072	4.075	4.075	4.074	4.073	4.074	0	0	0	0	0.001	0.001	0.001
8:38:36 AM	90	90	90	90	90	90	90	4.074	4.074	4.074	4.072	4.074	4.073	4.074	0	0	0	0	0.001	0	0
8:38:37 AM	90	90	90	90	90	90	90	4.077	4.074	4.074	4.073	4.073	4.073	4.073	0	0	0	0	0.001	0.001	0
8:38:38 AM	90	90	90	90	90	90	90	4.074	4.072	4.075	4.073	4.075	4.073	4.074	0	0	0	0	0.001	0	0
8:38:39 AM	90	90	90	90	90	90	90	4.075	4.073	4.076	4.075	4.074	4.075	4.073	0	0	0	0	0.001	0.001	0
8:38:40 AM	90	90	90	90	90	90	90	4.074	4.073	4.071	4.074	4.075	4.074	4.074	0	0	0	0	0.001	0.001	0
8:38:41 AM	90	90	90	90	90	90	90	4.075	4.072	4.075	4.072	4.074	4.074	4.073	0	0	0	0	0.001	0.001	0.001
8:38:42 AM	90	90	90	90	90	90	90	4.074	4.073	4.074	4.075	4.075	4.074	4.074	0	0	0	0	0.001	0.001	0
8:38:43 AM	90	90	90	90	90	90	90	4.074	4.073	4.075	4.074	4.075	4.074	4.075	0	0	0	0	0.001	0.001	0
8:38:44 AM	90	90	90	90	90	90	90	4.074	4.073	4.073	4.073	4.074	4.075	4.074	0	0	0	0	0.001	0.001	0
8:38:45 AM	90	90	90	90	90	90	90	4.074	4.074	4.073	4.074	4.073	4.074	4.073	0	0	0	0	0.001	0.001	0
8:38:47 AM	90	90	90	90	90	90	90	4.073	4.073	4.074	4.074	4.074	4.073	4.075	0	0	0	0	0.001	0	0
8:38:48 AM	90	90	90	90	90	90	90	4.075	4.075	4.075	4.072	4.073	4.073	4.074	0.001	0	0	0	0.001	0	0
8:38:49 AM	90	90	90	90	90	90	90	4.074	4.073	4.073	4.073	4.075	4.075	4.074	0	0	0	0	0.001	0.001	0
8:38:50 AM	90	90	90	90	90	90	90	4.074	4.074	4.075	4.075	4.075	4.074	4.074	0	0	0	0	0.001	0.001	0
8:38:51 AM	90	90	90	90	90	90	90	4.074	4.073	4.075	4.074	4.074	4.075	4.074	0	0	0	0	0.001	0.001	0
8:38:52 AM	90	90	90	90	90	90	90	4.073	4.074	4.075	4.074	4.076	4.071	4.073	0	0	0	0	0.001	0	0
8:38:53 AM	90	90	90	90	90	90	90	4.075	4.074	4.074	4.074	4.076	4.074	4.073	0	0	0	0	0.001	0.001	0
8:38:54 AM	90	90	90	90	90	90	90	4.075	4.073	4.075	4.073	4.076	4.073	4.073	0	0	0	0	0.001	0.001	0
8:38:55 AM	90	90	90	90	90	90	90	4.074	4.074	4.075	4.073	4.074	4.075	4.073	0	0	0	0	0.001	0	0
8:38:56 AM	90	90	90	90	90	90	90	4.074	4.072	4.075	4.072	4.076	4.075	4.073	0	0	0	0	0.001	0	0
8:38:58 AM	90	90	90	90	90	90	90	4.075	4.074	4.075	4.074	4.076	4.074	4.074	0	0	0.001	0	0.001	0.001	0
8:38:59 AM	90	90	90	90	90	90	90	4.075	4.074	4.073	4.074	4.075	4.073	4.074	0	0	0	0	0.001	0	0
8:39:00 AM	90	90	90	90	90	90	90	4.075	4.074	4.076	4.075	4.075	4.076	4.074	0	0	0	0	0.001	0.001	0

Appendix C - Project Schedule

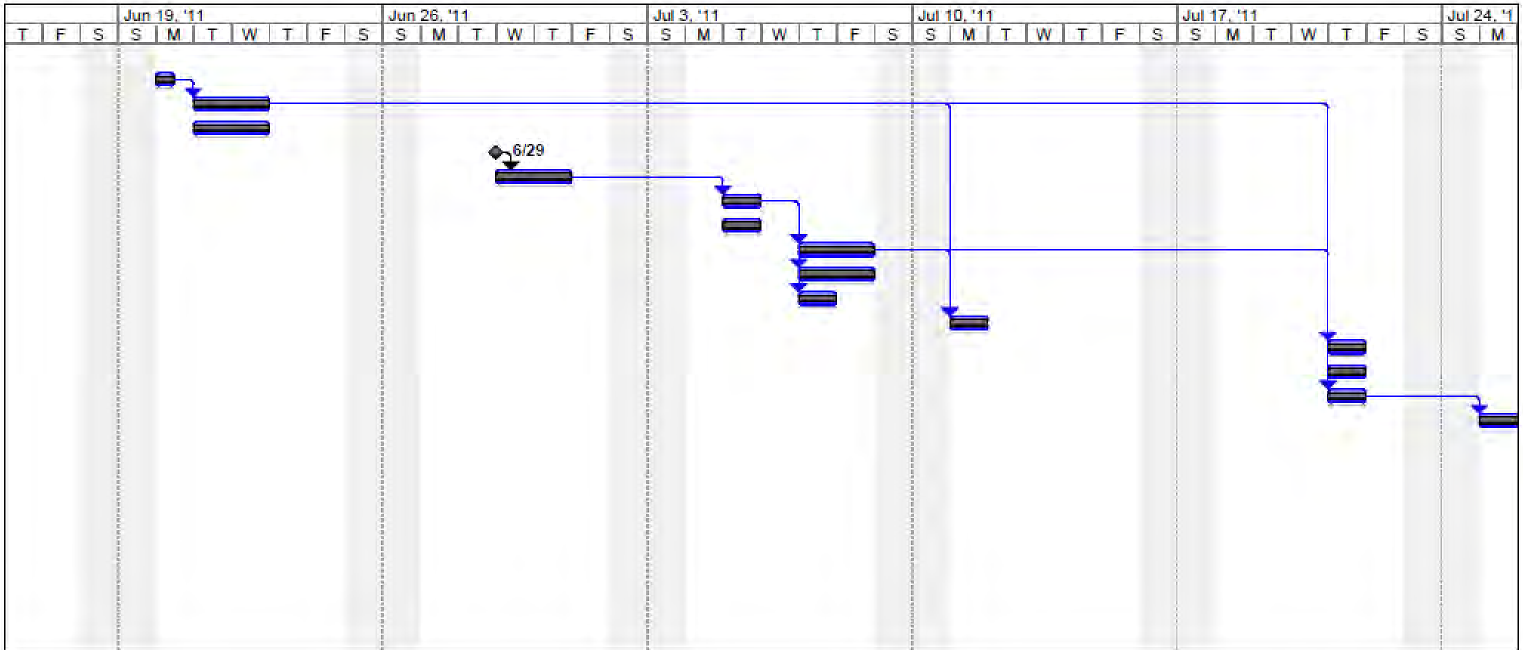
ID		Task Name	Duration	Start	Finish
1		Revised Project Proposal and Plan Submission	0 days	Mon 6/6/11	Mon 6/6/11
7	✓	Checkout of battery module communications hardware/software	0.5 days	Mon 6/20/11	Mon 6/20/11
8	✓	Removal of cells from battery module	2 days	Tue 6/21/11	Wed 6/22/11
10	✓	Review BMS schematics and operations manual	2 days	Tue 6/21/11	Wed 6/22/11
2		BMS-HIL Delivery	0 days	Wed 6/29/11	Wed 6/29/11
3	✓	BMS-HIL Transfer to BMS Lab Building From Dock	2 days	Wed 6/29/11	Thu 6/30/11
4	✓	BMS-HIL 208V, 3-phase plug installation	1 day	Tue 7/5/11	Tue 7/5/11
14	✓	Collect previous battery module test data to generate lookup table	1 day	Tue 7/5/11	Tue 7/5/11
5	✓	BMS-HIL Commissioning	2 days	Thu 7/7/11	Fri 7/8/11
6	✓	BMS-HIL Training	2 days	Thu 7/7/11	Fri 7/8/11
15	✓	Load lookup table into BMS-HIL and verify model function	1 day	Thu 7/7/11	Thu 7/7/11
13	✓	BMS-HIL and BMS software/hardware verification	1 day	Mon 7/11/11	Mon 7/11/11
9	✓	Creation of wire harness for connection to BMS	1 day	Thu 7/21/11	Thu 7/21/11
11	✓	Develop basic test plans and procedures for HIL testing	1 day	Thu 7/21/11	Thu 7/21/11
12	✓	Attach BMS to wire harness, attach wire harness to BMS HIL	1 day?	Thu 7/21/11	Thu 7/21/11
16	✓	BMS-HIL Testing (Room Temperature)	3 days	Mon 7/25/11	Wed 7/27/11
17	✓	BMS-HIL Testing (Cold-Temperature)	4 days	Thu 7/28/11	Tue 8/2/11
18	✓	BMS-HIL Fault testing (Room Temperature)	1 day	Wed 8/3/11	Wed 8/3/11
19	✓	Review and analysis of BMS-HIL testing results	5 days	Thu 8/4/11	Wed 8/10/11
25	✓	Advisor August Meeting	1 day	Fri 8/12/11	Fri 8/12/11
20	✓	Review and analysis of BMS-HIL cold-temp results	3 days	Mon 8/15/11	Wed 8/17/11
21		Draft final report (Limited Distribution)	3 days	Thu 8/18/11	Mon 8/22/11
22		Release draft final report to advisor for comment	0 days	Mon 8/22/11	Mon 8/22/11
23		TARDEC security review of final report for public release	7 days	Tue 8/23/11	Wed 8/31/11
24		Release of Public Version of Report	0 days	Wed 8/31/11	Wed 8/31/11



Project: ESENG 503 Project Plan (Ska
Date: Mon 8/15/11

Task | Milestone | External Tasks
Split | Summary | External Milestone
Progress | Project Summary | Deadline

Page 1



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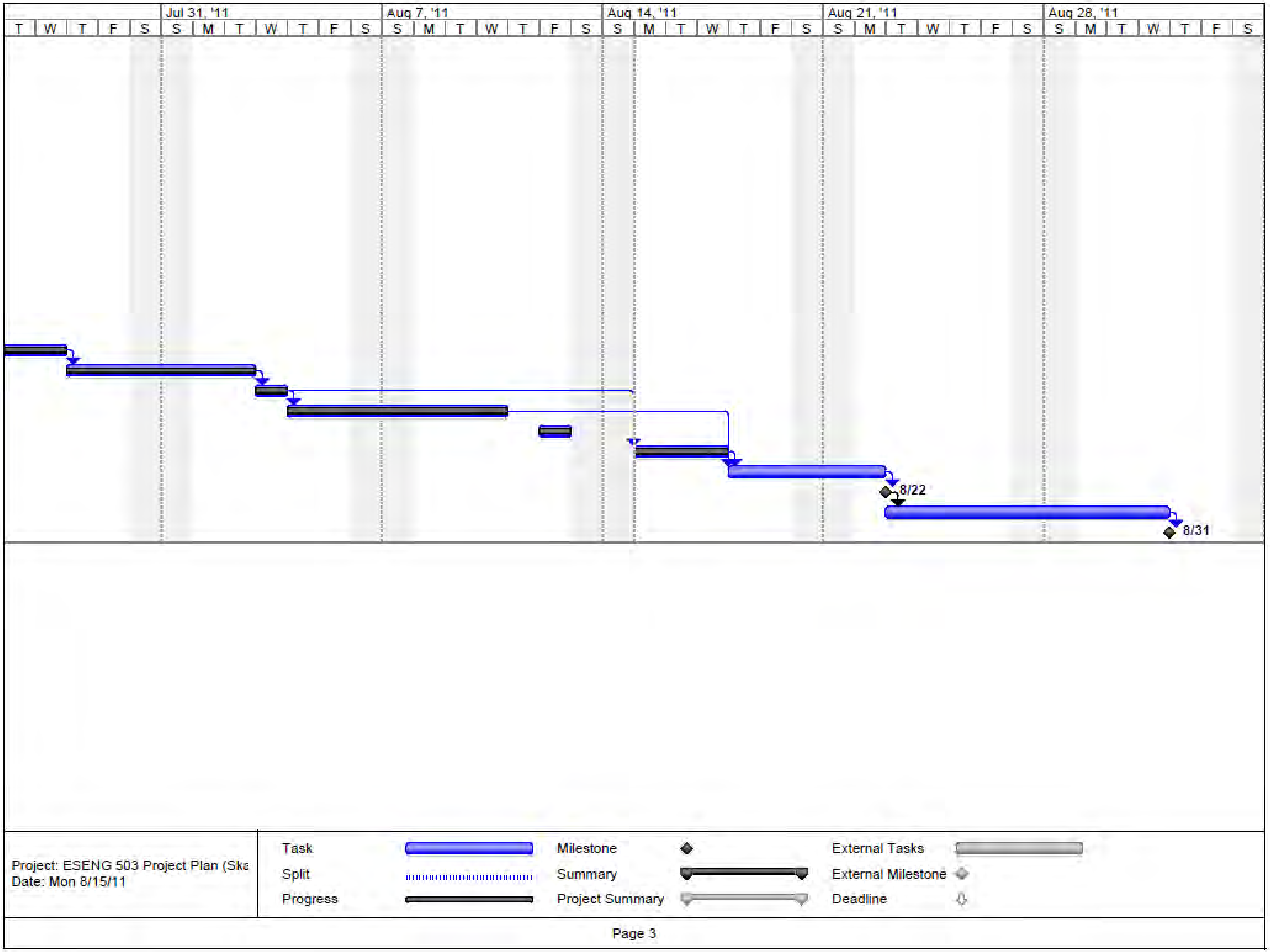
	Split		Summary		External Milestone	
	Progress		Project Summary		Deadline	

Page 2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Aug 7, '11
Aug 14, '11
Aug 21, '11
Aug 28, '11
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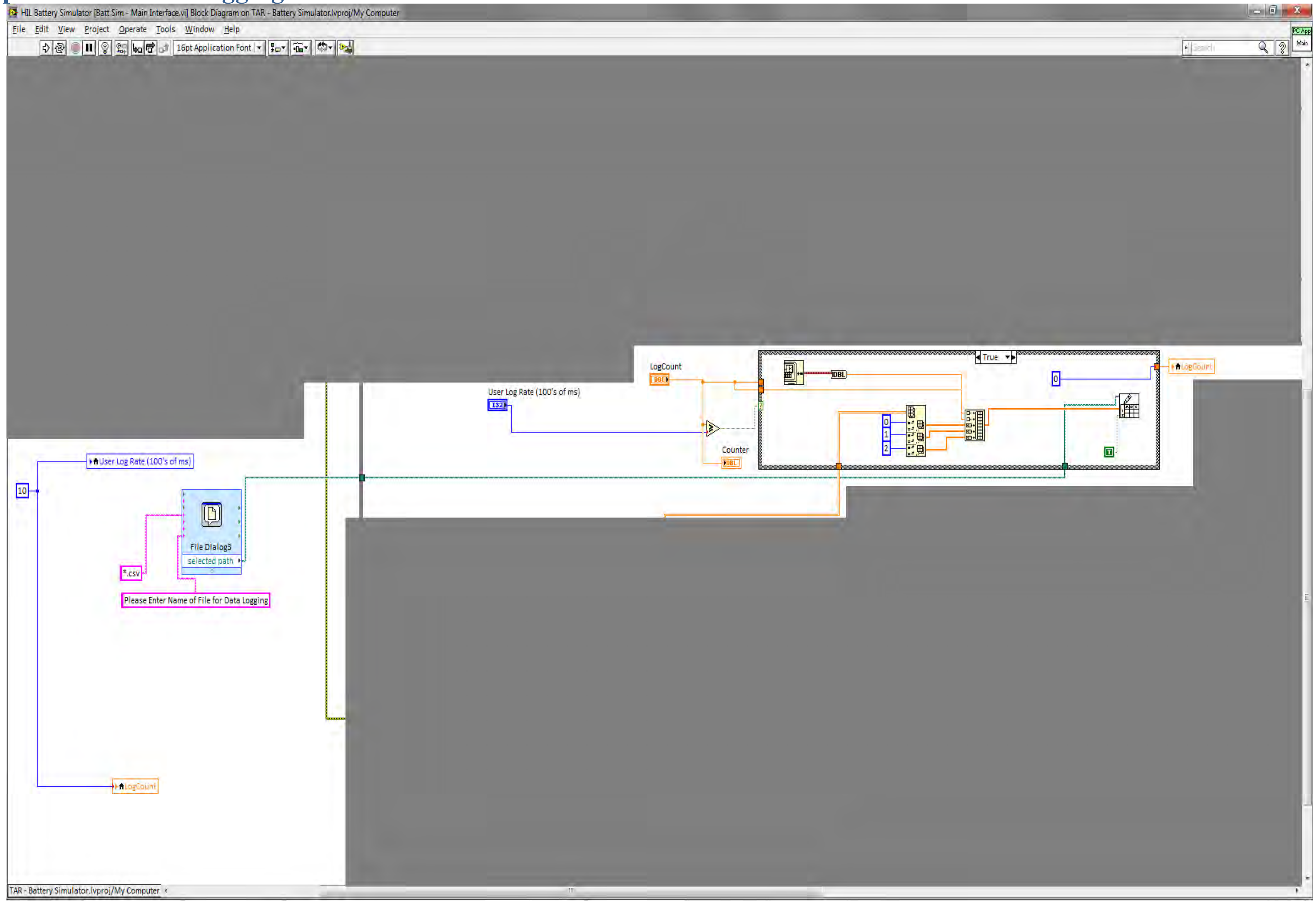
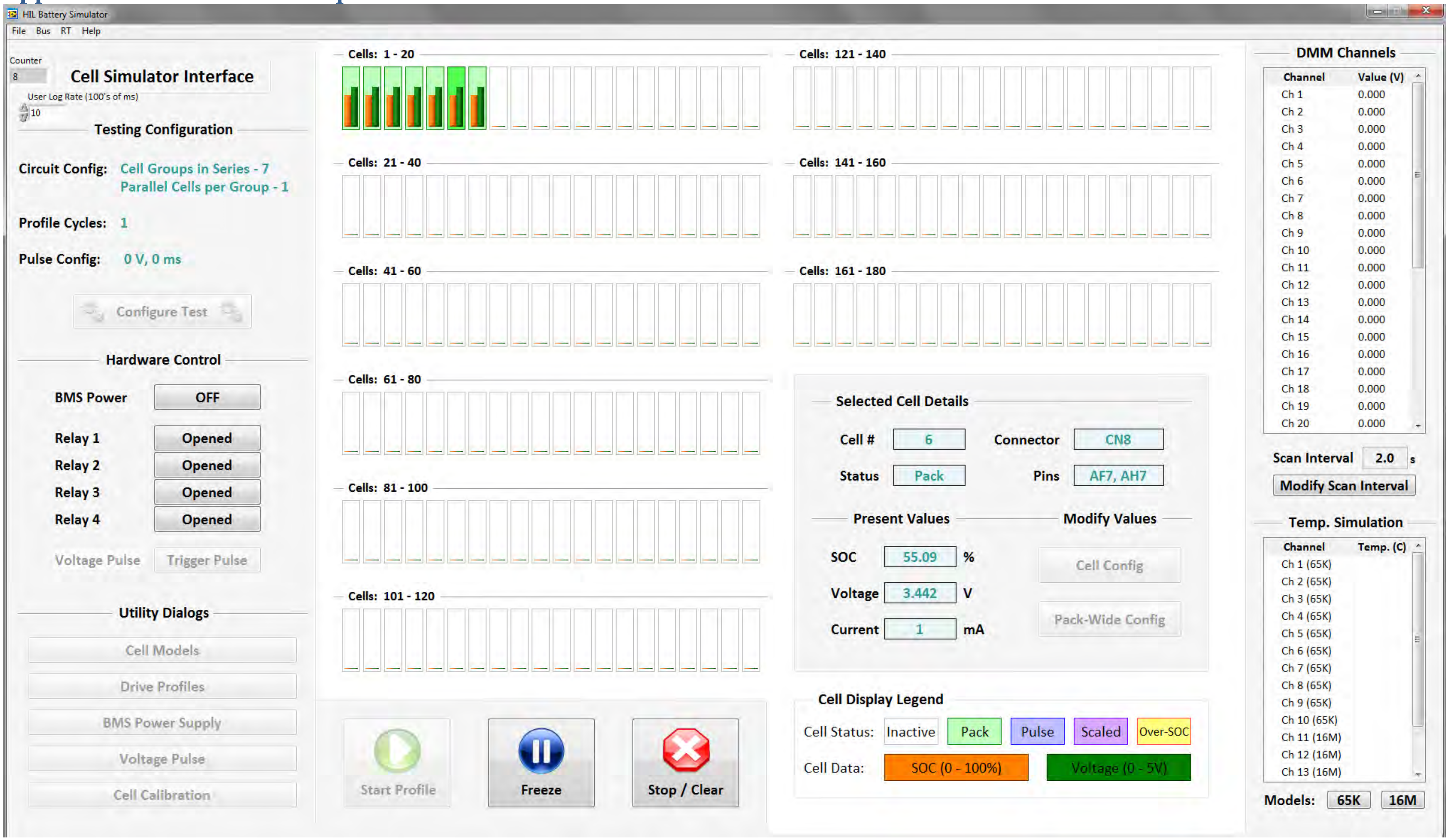
8/22
8/31
Project: ESENG 503 Project Plan (Ska
Date: Mon 8/15/11
Task
Split
Progress
Milestone
Summary
Project Summary
External Tasks
External Milestone
Deadline
Page 3

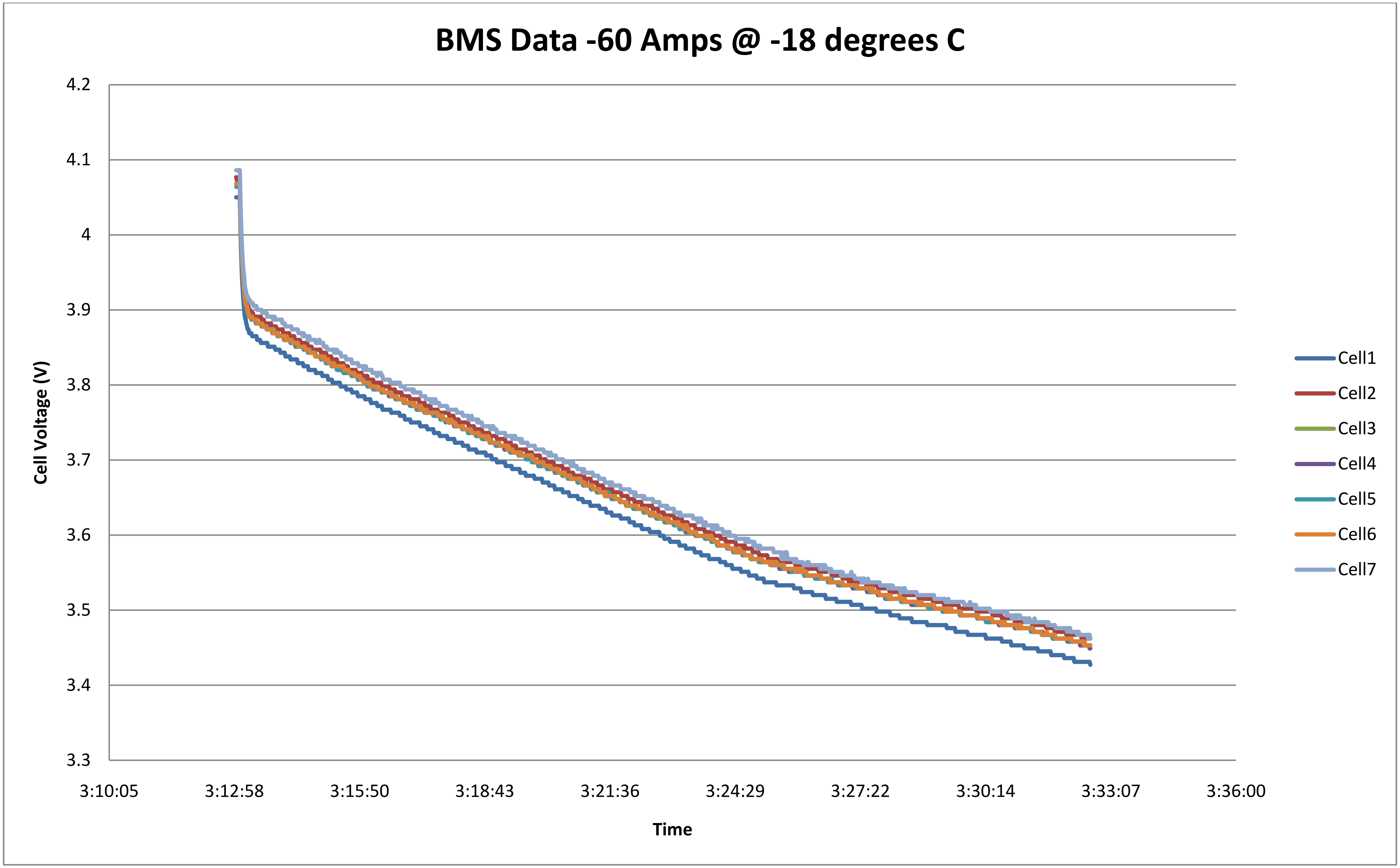
Appendix D - Data Logging Code

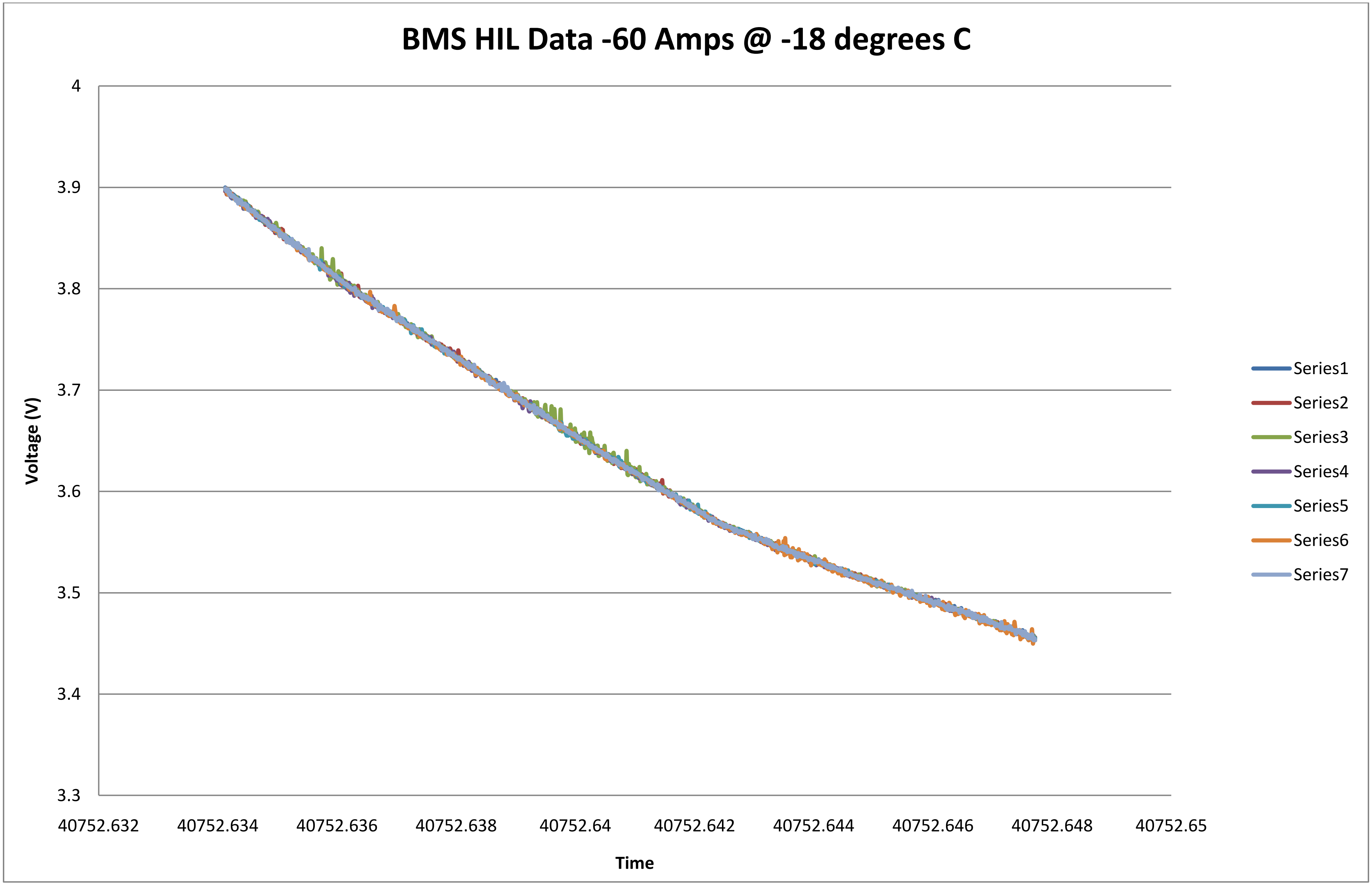


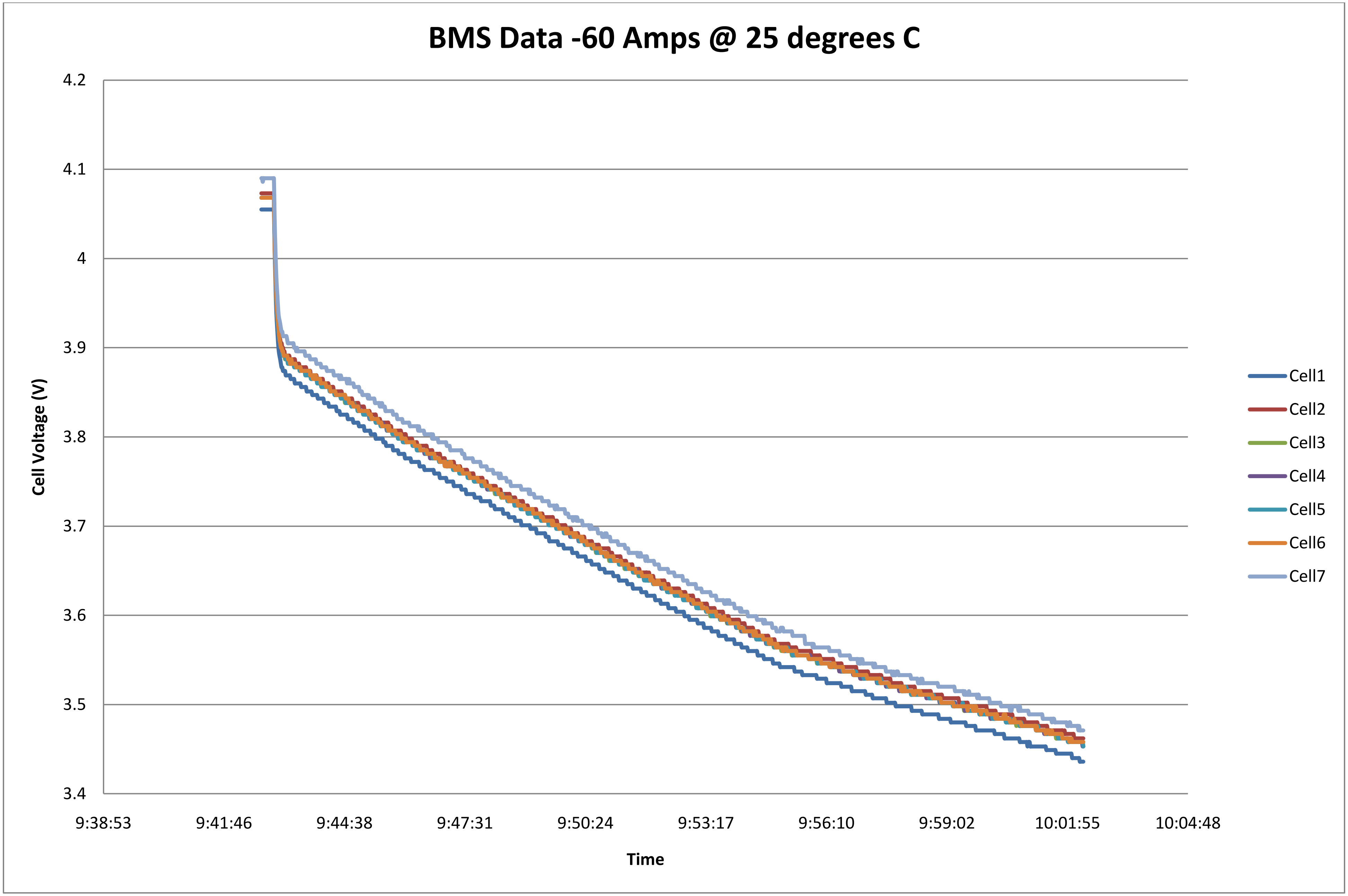
Appendix E – BMS HIL Graphical User Interface Screen Shot



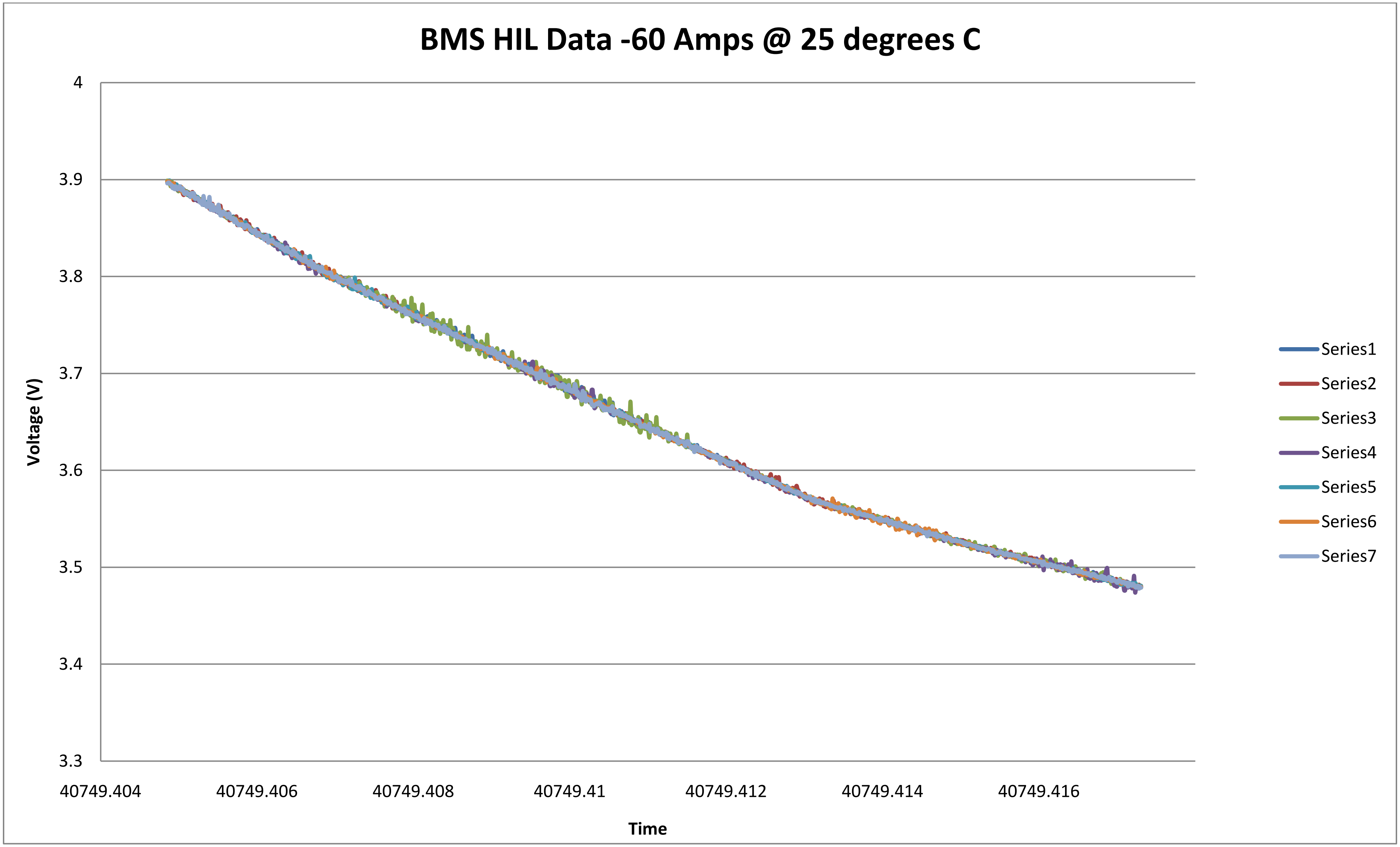
Appendix F – Test Data Graphs for -60 Amps at Room Temperature and Cold Temperature




BMS HIL Data -60 Amps @ -18 degrees C
Voltage (V)
4
3.9
3.8
3.7
3.6
3.5
3.4
3.3
40752.632
40752.634
40752.636
40752.638
40752.64
40752.642
40752.644
40752.646
40752.648
40752.65
Time
Series1
Series2
Series3
Series4
Series5
Series6
Series7



BMS Data -60 Amps @ 25 degrees C
4.2
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
Cell Voltage (V)
9:38:53
9:41:46
9:44:38
9:47:31
9:50:24
9:53:17
9:56:10
9:59:02
10:01:55
10:04:48
Time
Cell1
Cell2
Cell3
Cell4
Cell5
Cell6
Cell7


BMS HIL Data -60 Amps @ 25 degrees C
Voltage (V)
4
3.9
3.8
3.7
3.6
3.5
3.4
3.3
40749.404
40749.406
40749.408
40749.41
40749.412
40749.414
40749.416
Time
Series1
Series2
Series3
Series4
Series5
Series6
Series7

Appendix G – Cell Model

Cell Capacity			
30			
SOC (%)	**Voltage (V)**	**Charge Res (mOhms)**	**Discharge Res (mOhms)**
0	3.4	3.4	4.2
10	3.5	2.9	3.2
20	3.6	2.7	2.8
30	3.6	2.5	2.6
40	3.6	2.5	2.6
50	3.7	2.5	2.6
60	3.8	2.7	2.8
70	3.8	2.8	2.8
80	3.9	2.8	2.9
90	4.0	3.2	2.9
100	4.1	3.8	2.9

*Note: Data rounded to the nearest tenth

Appendix H – BMS HIL Experimental Test Plan

Background and Test Purpose:

The purpose of this test plan/procedure is to provide a test plan for Army battery management systems (BMS's) at the module level. Module cell voltages will be simulated using the BMS Hardware-in-the-Loop (BMS HIL) simulator and state of charge and DC resistances obtained from existing cell characterization and HPPC data. The voltage limits are set at 5V maximum per cell simulator up to 750V in series. For this test, 7 cell simulator channels will be used and connected in series to simulate a 28-V Lithium-Manganese-Oxide battery. The BMS being tested was extracted from a 28-V prototype GS Yuasa Lithium-Manganese-Oxide battery designed for the Army.

The test engineer is allowed to change the sequence of the tests as needed to accommodate test unit quantities or equipment availability.

BMS HIL Basic Information:

The BMS HIL is a highly flexible system for the real time simulation of the electrical and thermal properties of a battery down to the cell level for the evaluation of BMS's. The HIL test system can be used to independently evaluate/validate BMS under a variety of environmental conditions. The HIL test system being used for this project has the following characteristics:

- The system is capable of evaluating BMS for isolation monitoring, voltage monitoring, current monitoring, temperature sensing and cell balancing.
- The system is capable of simulating electrical failures (including broken/loose connections and isolation failure)
- The system has 170 cell simulators and is capable of emulating up to 16 temperature readings.
- Each cell simulator provides a galvanically isolated voltage from 0 to 5V in 2mV increments and is capable of handling a 150 mA load.
- Individual cell simulators are capable of being connected in series to simulate a full pack with a nominal voltage of 600V DC (with a maximum voltage of at least 750V DC).
- The HIL test system provides 25 independent voltage measurements.
- The system provides 24V to power the BMS during testing.
- Communication between the HIL system and BMS shall be via Serial and/or controller area network (CAN).

Appendix I – BMS HIL Experimental Test Plan

Document Test Equipment Configuration – For BMS

1. Record test equipment ID, environmental chamber ID, cell simulator channels, and calibration verification date.
2. Document any other equipment that might be needed to reproduce this test.
3. The BMS HIL will record simulated cell voltage, cell SOC relative to the inputted cell model, cell simulator channel current (up to 250 mA draw), and time.
4. Data will be collected from the RS-232 BMS data logging and monitoring software program.

Visual Inspection of the BMS

Using a checklist format:

1. Document voltage sensor locations and ID's.
2. Check power supply configuration and record connection points
3. Check/record data communications and output whilst connected to the battery cells and module.
4. Take pictures of as received unit before and after tear-down and BMS extraction.
5. Take thermal images of the BMS in its dormant steady-state condition.
6. Examine BMS for damage or physical anomalies; record observations.
7. Record any changes made to the BMS hardware/software to accommodate testing and interfacing with the BMS HIL.
8. Complete Attachment I

1. Communications & Sensors Checkout

Connect the BMS while still inside battery module to the computer to ensure communication connection. Disassemble battery module and remove battery cells. Document part locations with labeling and photographs, and catalog all parts into individual plastic storage bags. Power BMS with external power supply and test communications for responsiveness. Connect BMS to BMS HIL cell simulators, and check communications for cell data output. Verify BMS power supply is isolated from the cell simulator voltages using a multi-meter.

2. Fault Testing

Simulate faults on each cell simulator based on the BMS fault indicator list provided by the battery/BMS manufacturer to determine the BMS's response to these events. Faults tested may include overvoltage, under-voltage, over-temperature, cell voltage imbalance, and cell over-pressure.

3. Simulated Charge/Discharge Rate at 25^{o}C (In Chamber)

BMS functionality will be assessed at room temperature using simulated module charge and discharges at C/20, C, 2C, 4C, and 8C rate based on the cell capacity of the battery module. Thermal imaging and photographs will be taken as appropriate. The simulations will be abbreviated to look at portions of the profile including, top of charge, 1 or 2 segments of middle of charge, and end of charge

4. Simulated Charge/Discharge Rate at -20^{o}C (In Chamber)

BMS functionality will be assessed at the minimum BMS operating temperature using simulated module charge and discharges at C/20, C, 2C, 4C, and 8C rate based on the cell capacity of the battery module. Thermal imaging and photographs will be taken as appropriate. The simulations will be abbreviated to look at portions of the profile including, top of charge, 1 or 2 segments of middle of charge, and end of charge.